# Probing highly compressed degenerate matter and matter at extreme Gbar pressures at NIF

**Presentation to**

**NIF User Group**

**Feb 13, 2012**

**A. Kritcher**

*Liaison scientist for NIF proposal, Postdoctoral Fellow*

***P. Neumayer, R. Falcone,*** *D. Swift, J. Hawreliak, H. Lee, R. Redmer, E. Foerster, C. Fortmann, S. Le Pape, G. Hays, S. Rose, R. Hemley, R. Jeanloz, D. Hicks, P. Cellier, J. Eggert, D. Milathianaki, T. Doeppner, O. Landen, G. Collins, S. Glenzer*



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# Matter at >20x solid compression and pressures of Gbar can only be reached and probed with XRTS and radiography at NIF

- **Matter at extreme densities occurs in astrophysical objects such as giant gas planets and highly evolved stars**
  - At extreme densities matter becomes metallic. The ions are strongly coupled due to the small inter-particle distance and the high charge state.
  - Electron coupling decreases at higher density, due to the increasing Fermi-energy
- **Matter at extreme pressures of Gbars (and higher temp) occurs in the cores of super-giant planets and stars**
  - Fundamental physics including EOS and ionization of condensed matter up to Gbar pressures is important for understanding the evolution of these astrophysical bodies

**Measurement of microscopic properties & plasma parameters** ➡ **X-ray scattering & X-ray radiography**

# These joint proposals include many outside collaborators from several institutions

- **GSI, Germany:**
- ***P. Neumayer***

- **Univ. of California Berkeley, USA/LBNL, USA:**
- ***R. Falcone****, R. Jeanloz*

- **LLNL, USA**
- *D. Swift, J. Hawreliak, S. Le Pape, D. Hicks, P. Cellier, J. Eggert, T. Doeppner, O. LandenG. Collins, S. Glenzer*

- **LCLS, USA**
- *H. J. Lee, D. Milathianaki, G. Hays*

- **Univ. of Jena, Germany**
- *E. Foerster, et al.*

- **Univ. of Rostock, Germany**
- *R. Redmer, et al.*

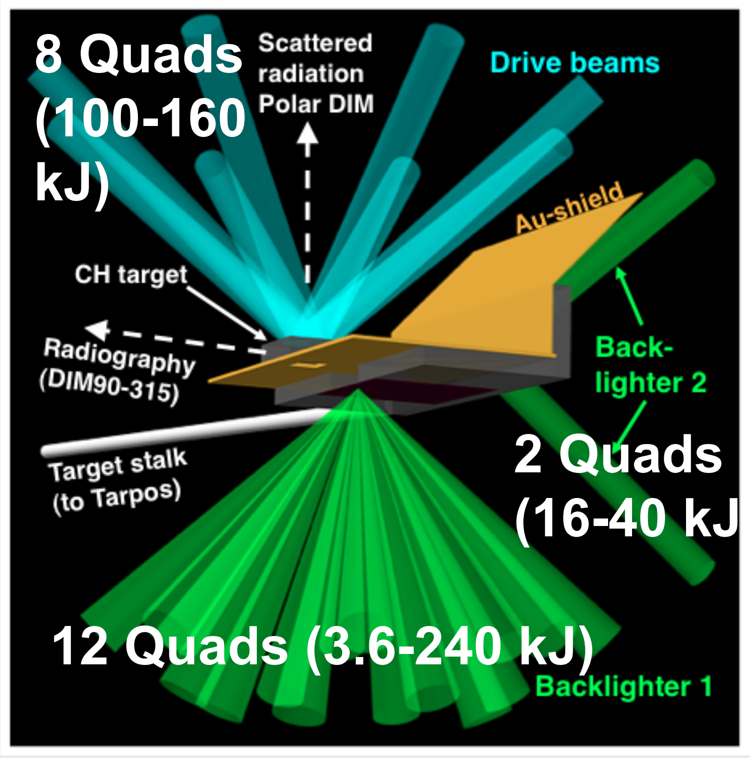
- **Univ. of California Los Angeles, USA**
- *C. Fortmann*

- **Imperial College London**
- *S. Rose, et al.*

- **Carnegie Institute of Washington**
- *R. Hemley, et al.*

# Experiments at NIF will compress matter to densities of >20x solid, while staying on a low isentrope, using multiple shocks

**CH will be directly driven in a planar geometry and probed with x-rays**




***A new spectrometer snout for XRTS is being developed…***

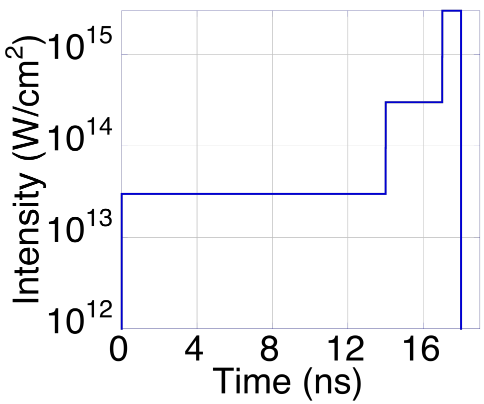
***Laser Requirements:***

***Drive (8 quads):*** *3-5kJ/beam, focus= 1mm*

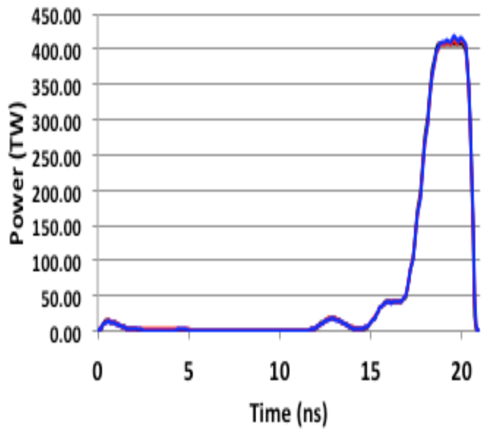
***XRTS Probe beams (12 quads):*** *75/beam (88ps impulse) or 4-5 kJ/beam (NIF Pulse), focus= 250µm*

***Radiography Backlighter (2 quads):*** *4-5 kJ/beam (NIF Pulse), focus= 1mm*

***Drive Pulse Shape:***



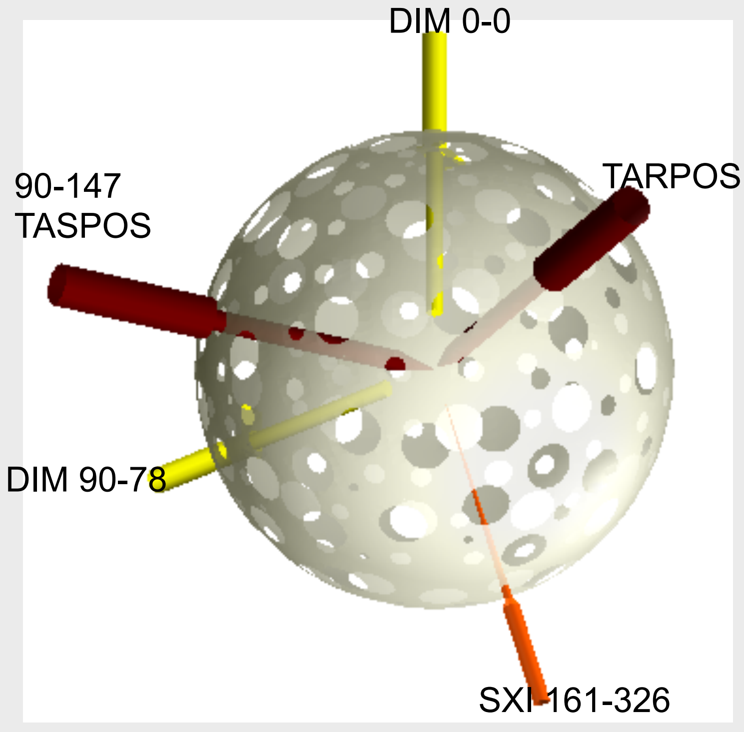

***BL Pulse Shape (NIF):***




*(PI) P. Neumayer, et al.*

# Diagnostic configuration and compatible NIF platforms for planar high compression experiments

## Experimental layout, w.r.t. target chamber




## *Diagnostics Configuration:*

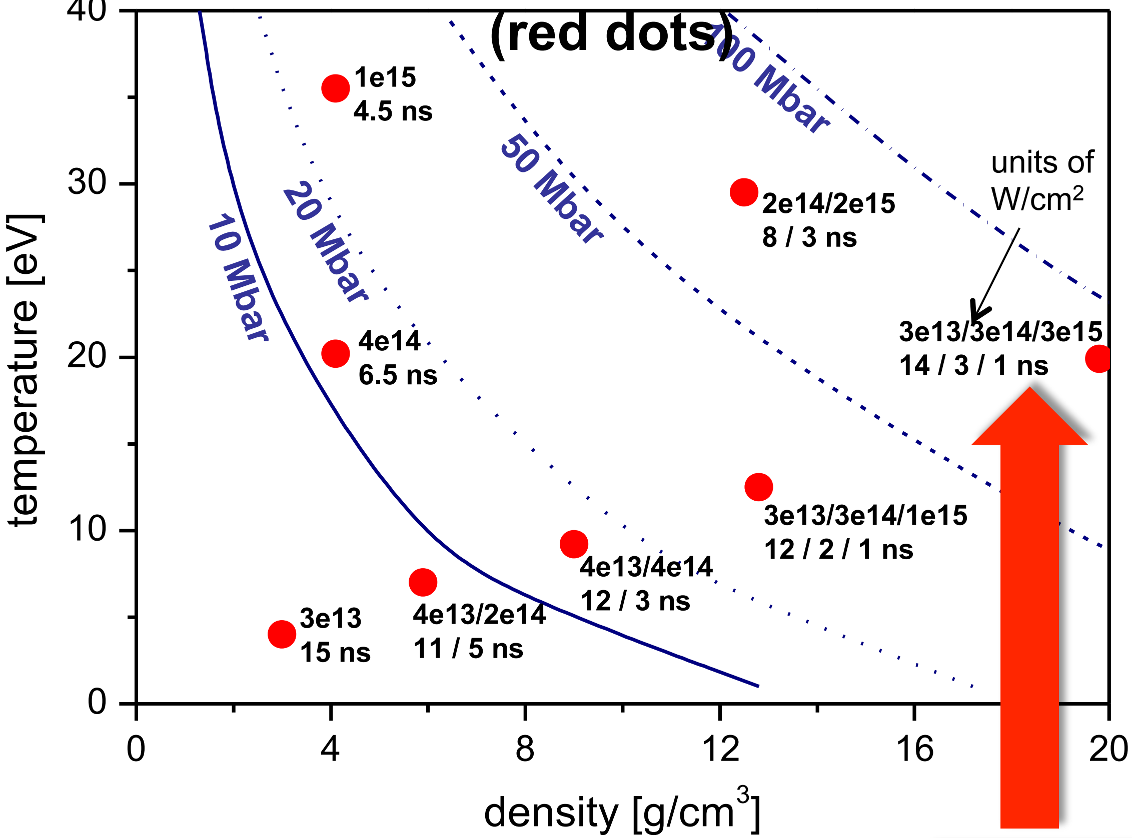
| Diag | Location | Priority | Type | Calib |
|---|---|---|---|---|
| GXD or hGXI | 90-78 | Essential | 3 | Pre-Shot |
| hGXI or GXD +Supersnout 2 or MAHS | 0-0 | Essential | 1 | Pre-Shot |
| SXI 1 | 161-326 | Ride-along | 3 | Pre-Shot |

## *Compatible diag configurations:*

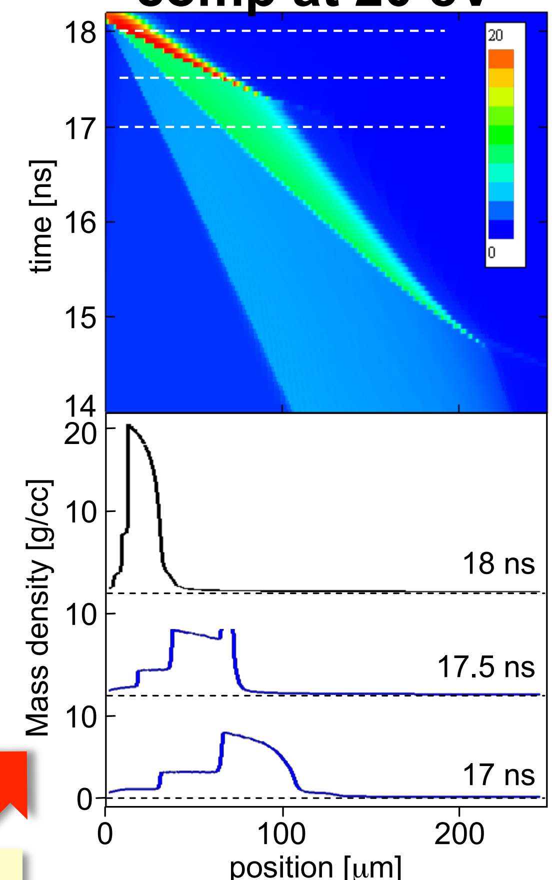
1) (DT4 for DT & ConAW) shown to the left
2) DT3 for DT & ConAW
3) DT2 for DT & keyhole

# Pulse shaping enables creation of highly compressed and strongly coupled matter at relatively low temperatures

## Densities and temperatures at shock coalescence single- or multiple shocks (red dots)




## We can reach 20x comp at 20 eV




3-shock comp

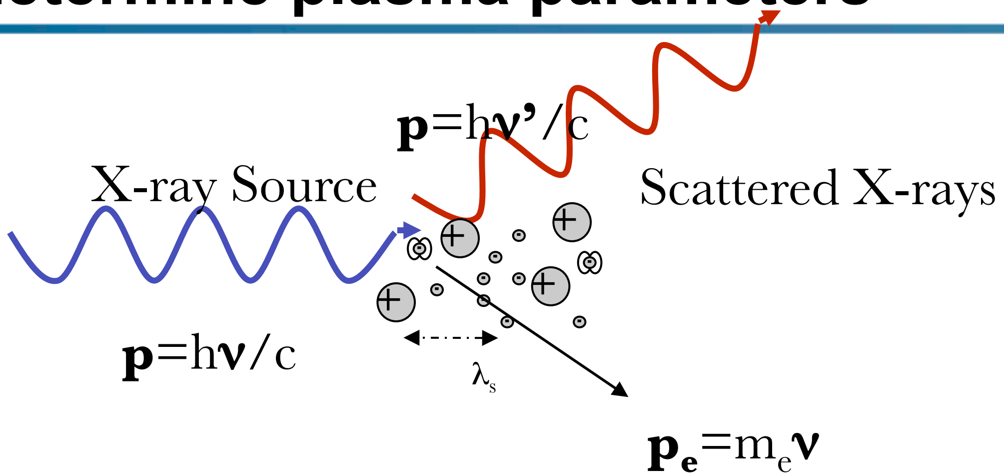
*(PI) P. Neumayer, et al.*

# In these experiments X-rays are scattered from plasma electrons to determine plasma parameters

## X-ray Scattering

We Scatter x-rays from electrons in the plasmas.

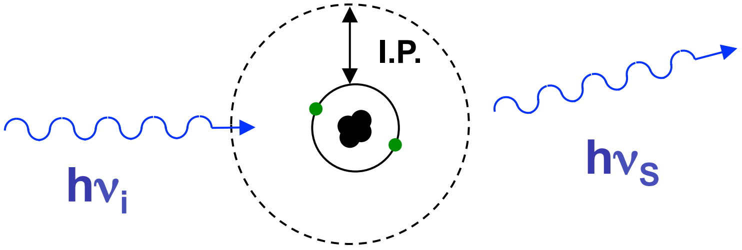
Electrons absorb the photon, oscillate, and re-emit the x radiation.




## Elastic (Rayleigh):

E of incident photon is conserved

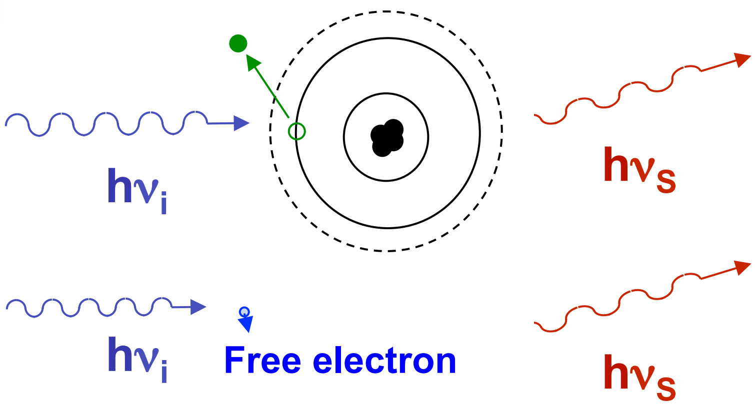
-Tightly Bound e$^-$ :
Binding Energy > Compton Energy ($\Delta E_c$)




## Inelastic (Compton or Plasmon):

-Weakly Bound e$^-$ :
Binding Energy < Compton Energy ($\Delta E_c$)

-Free e$^-$




O. L. Landen et al., JQSRT 71, 465 (2001)

# The non-collective and collective scattering will be applied to observe the micro and macroscopic motion of the electrons

Scattering Parameter: $\alpha$

$$\alpha = \frac{1}{k\lambda_s} \propto \frac{\lambda}{\lambda_s}$$

$$k = \frac{4\pi}{\lambda_o}\sin(\theta/2)$$

Plasma Screening Length: $\lambda_S$

**Fermi-degenerate Plasma:**

$$\lambda_{TF} = \left(\frac{\hbar^2}{4m_e e^2}\left(\frac{\pi}{3n_e}\right)^{1/3}\right)^{1/2}$$

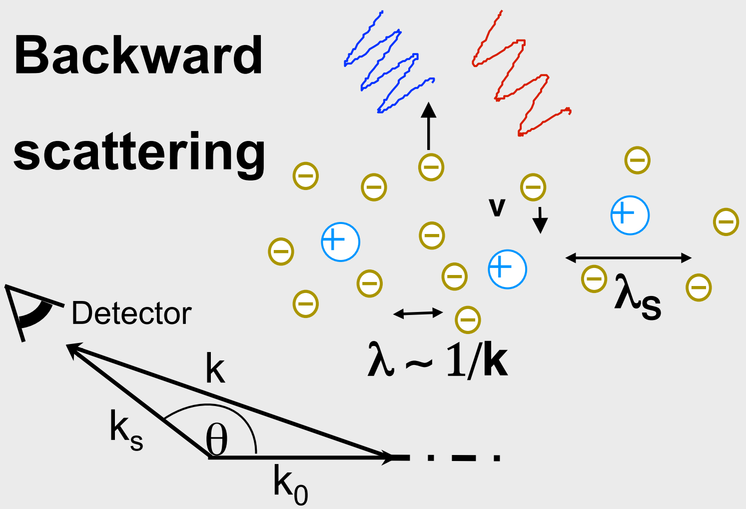
**Classical Plasma:**

$$\lambda_D = \left(\frac{\varepsilon_o k T_e}{n_e e^2}\right)^{1/2}$$

## Non-Collective Scattering

Probing: $\lambda < \lambda_S$ ($\alpha < 1$)

**Backward scattering**

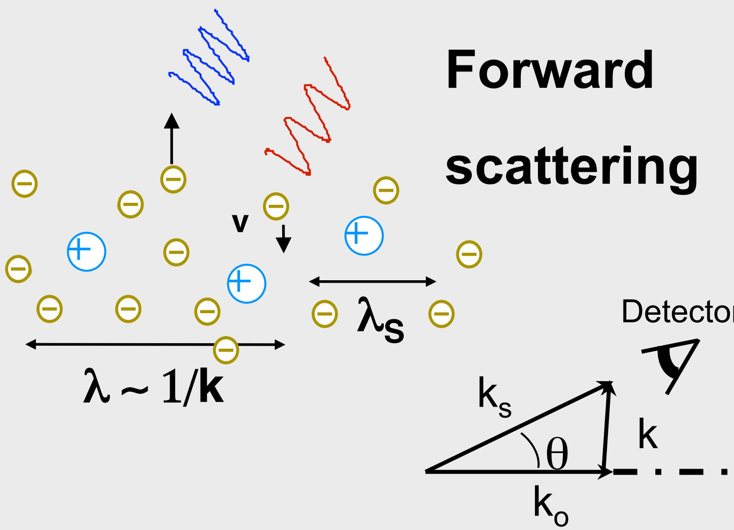



S. H. Glenzer et al., PRL (2003)

## Collective Scattering

Probing: $\lambda > \lambda_S$ ($\alpha > 1$)

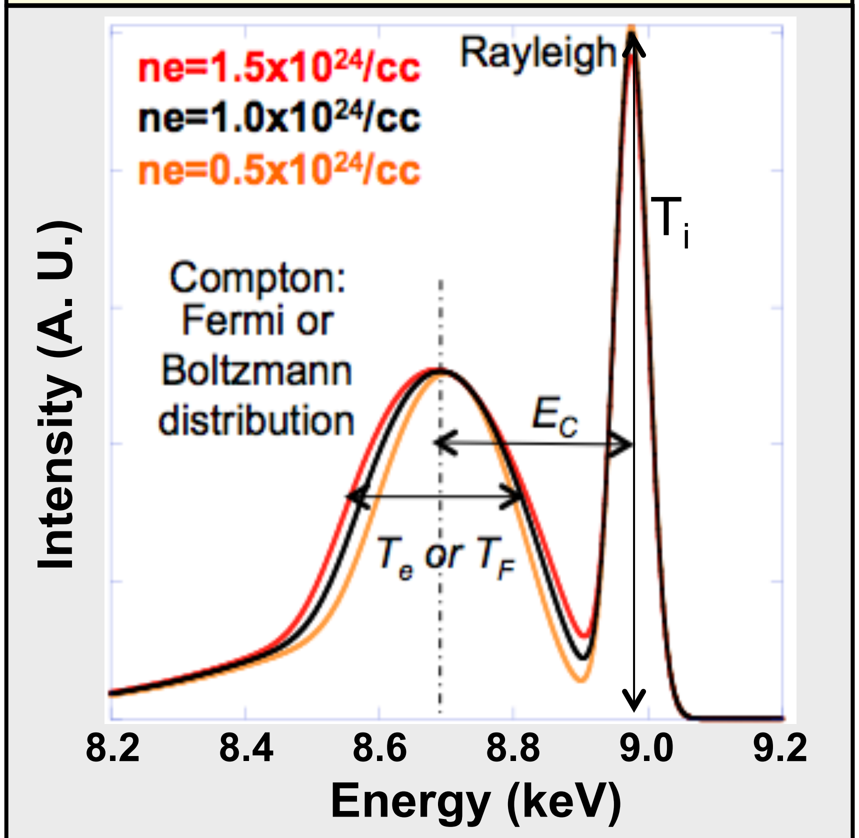
**Forward scattering**



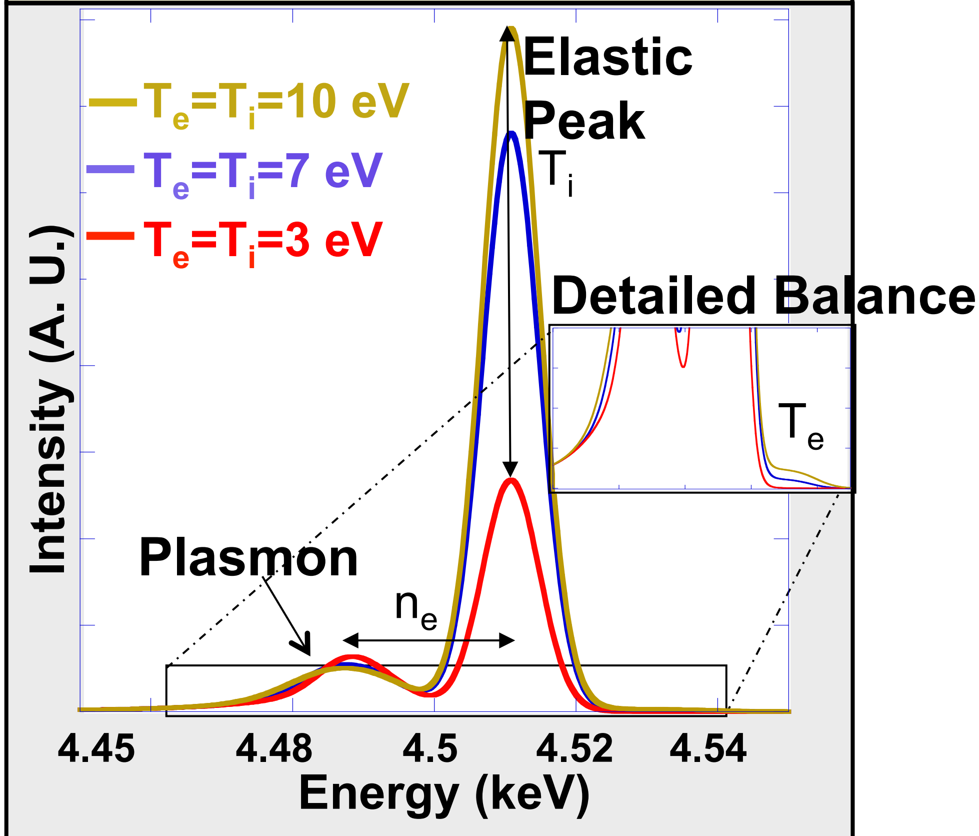

S. H. Glenzer et al., PRL (2007)

# The plasma parameters can be determined from the shape of the scattered spectra

## Non-Collective Scattering Spectra




## Collective Scattering Spectra




***Partially Degenerate:***
Width → $T_F$ ($n_e$)
Steepness of the red wing → $T_e$
***Non Degenerate:***
Width → $T_e$

Detailed Balance: (Blue Feature) Take energy from plasmon wave ~$e^{-\Delta\omega/kT}$

$$\Delta \omega \sim \omega_{pe} \propto n_e^{1/2}$$

# The Intensity of the elastically scattered X-rays is Directly Related to the Structure Factors

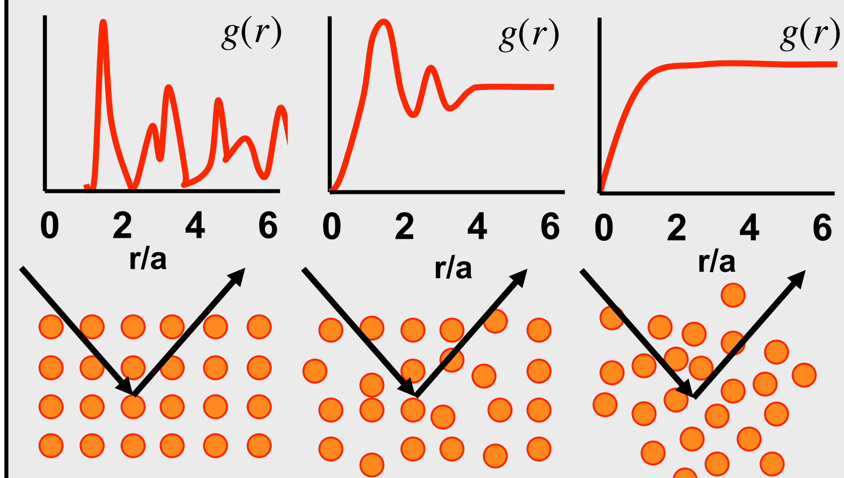
**Total Cross-Section Includes Free, Tightly, and Weakly bound States**

$$\frac{{}^{*}d^2\sigma}{d\Omega d\omega} = \sigma_T \frac{k_1}{k_o} S(k,\omega)$$

$$S(k,\omega) = \underbrace{Z_f S^{o}_{ee}(k,\omega)}_{\text{Electron Feature}} \underbrace{+Z_c \int \tilde{S}_{ce}(k,\omega-\omega')S_{ce}(k,\omega')d\omega'}_{\text{Bound-Free Feature}} \underbrace{+\left|f_1(k)+q(k)\right|^2 S_{ii}(k,\omega)}_{\text{Ion Feature}}$$

**The Scattering Intensity Depends on the Material Structure**

***$S_{ii}(k,\omega)$*:** Probability of finding an ion at a given distance from another ion (*k* space).




**Solid Crystalline Structure** **Liquid-Like Structure** **Gas-Like Structure**

When atoms are less structured there is more of a probability to scatter at an arbitrary angle (less coupling) ==> S(k,w) becomes smooth

*J. Chihara, J. Phys. Condens. Matter **12**, 231 (2000)

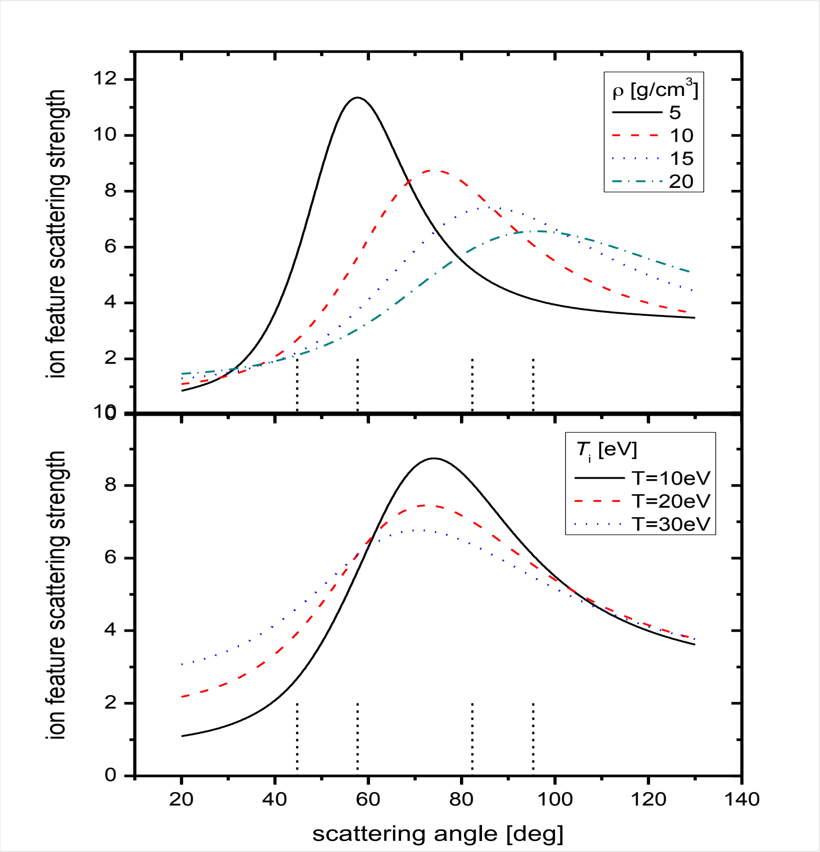
# By probing multiple scattering angles we can study ion structure in highly degenerate plasmas

- Study ion correlations via elastically scattered photons off of bound electrons (measure scattered intensity)

- Position of the correlation peak:
  → Wigner-Seitz radius
- Sharpness of the correlation peak:
  → Degree of ion-ion coupling

- Scattering at large k (17.5 keV) where Sii ~1 will enable characterization of $\left|f(k)+q(k)\right|^2$

**We can test models of material structure at high Temp & densities that predict ion-ion correlations and calculate EOS (DFT-MD)**



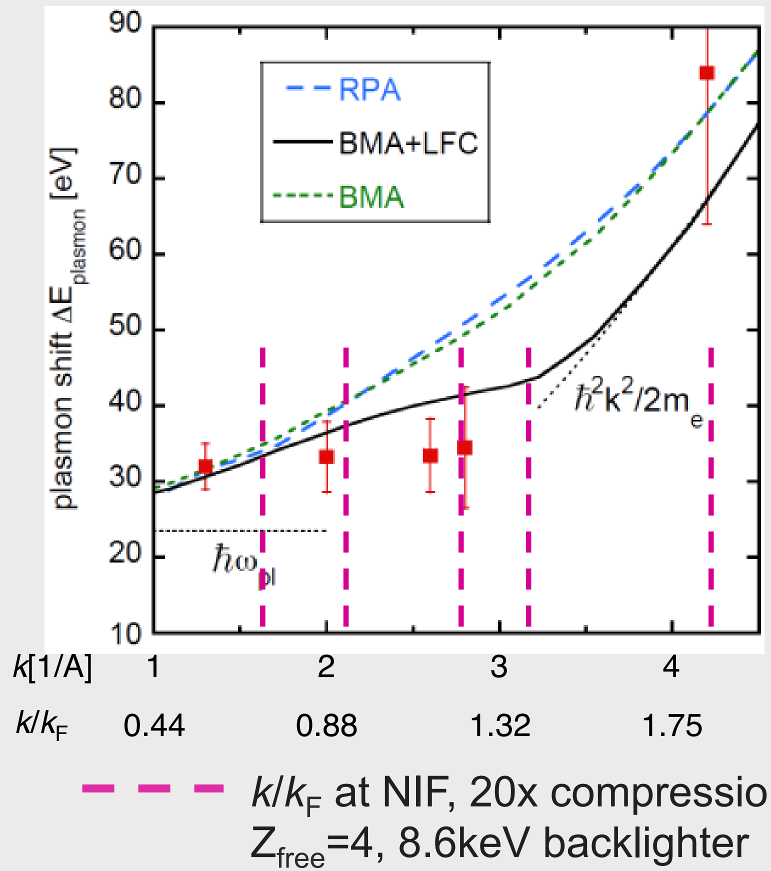

*Neumayer (PI), Kritcher, Glenzer, Lee, et al*

*(PI) P. Neumayer, et al.*

# By probing multiple scattering angles we can study electron electron correlation in highly degenerate plasmas

- Collective scattering includes scatter of electron plasma waves (plasmons)
- RPA is used to calculate the plasmon dispersion
- Deviation from mean field theory (RPA) due to short range local field corrections for the electrons results in a reduced plasmon shift or kinetic energy ($e^-$ *more correlated*)
- Dispersion measurements in dense plasmas are directly related to $e^-$ coupling, i.e. internal energy

**Energy shift of plasmon from the incident probe energy**

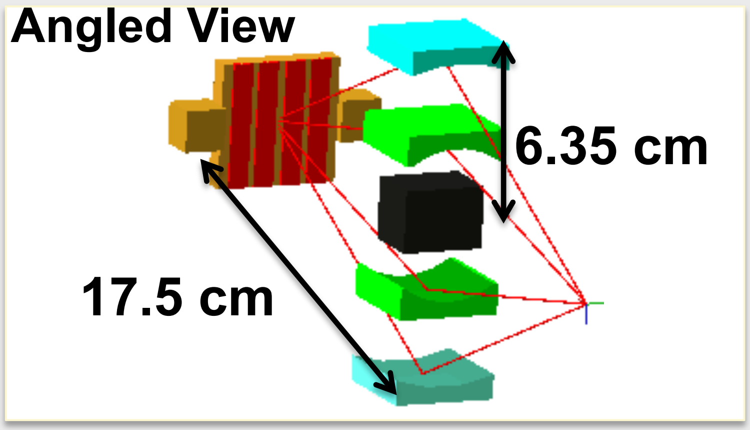


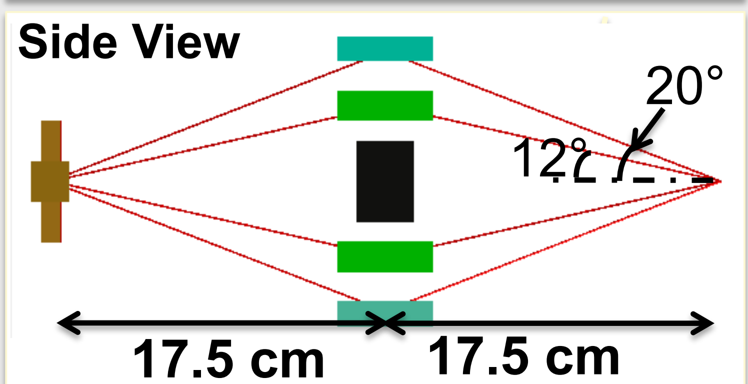

P. Neumayer et al., PRL 105, 075003 (2010)

*(PI) P. Neumayer, et al.*

# A new multi-angle spectrometer will enable simultaneous probing of four scattering angles or k-vectors

## New Multi-angle XRTS Spectrometer




LiF(200) ROC: 60 mm, 7.4-10.6 keV, first order

HOPG ROC: 38 mm, 7.3-10.7 keV, first order

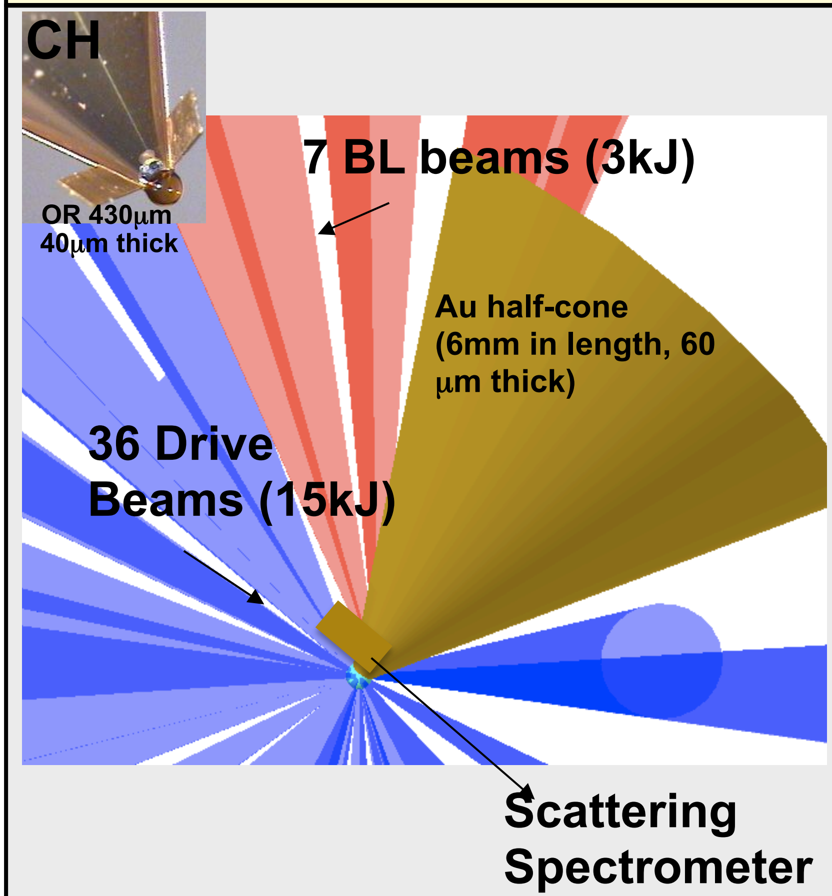
## Specs for spectrometer snout

- Angles: ± 20 deg± 12 deg
- HOPG used for high reflectivity (3mrad), LiF is used for better energy and spatial resolution
- Crystals (7x5cm) will be cylindrically/ conically bent with $\Omega=7\times10^{-5}$/xtal $=3\times10^{-4}$total
- Gated MCP's, IP surrounding MCP and full IP option
- Blast shield, filter options before the crystals and at the MCP, Tungsten block for direct line of sight of TCC to the MCP

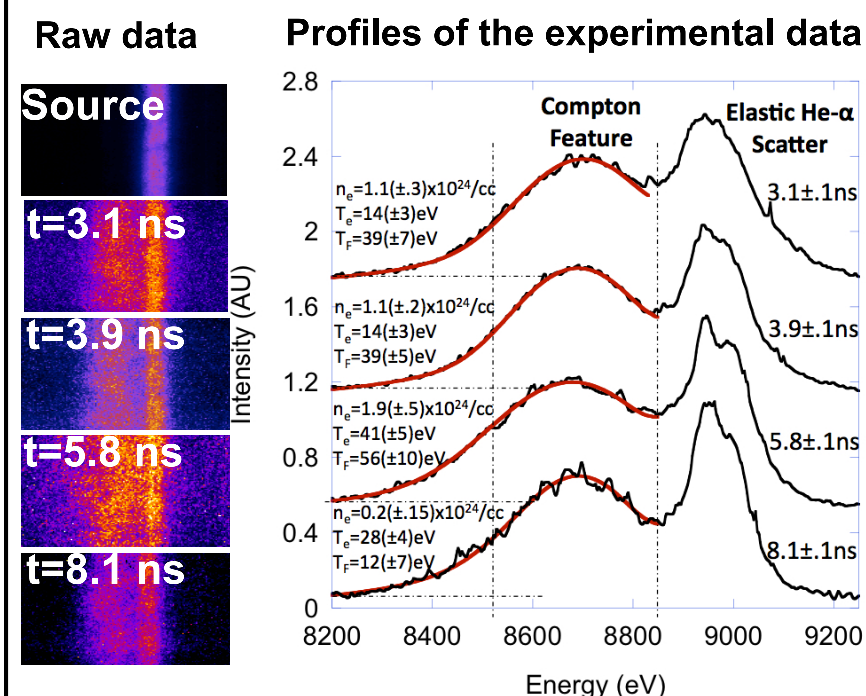
*Fabrication through Artep.*

# Highly compressed and degenerate matter has been probed with XRTS from spherically imploded capsules at Omega

## Schematic of the experimental configuration




## Compressions of x7 and x13 times solid density in CH and Be have been probed



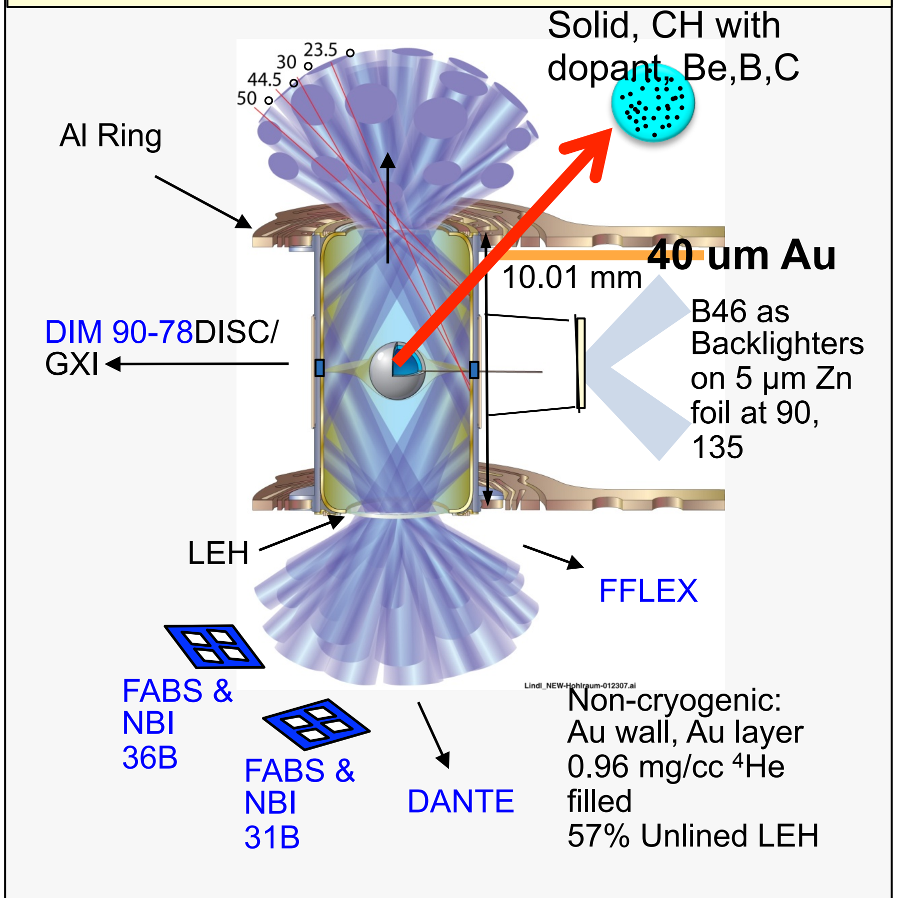

**SNR of up to >200 (A. kritcher, et al. PRL)**

→ Infer plasma properties such as adiabat and degree of ion-ion coupling (>5)

The high SNR of the data and sensitivity of the Compton-red wing enabled model independent determination of Te and ne (~20% for $n_e$ and Te, and 13% for adiabat)

# NIF enables the creation of conditions to study the cores of exoplanets (up to 2Gbar) and brown dwarfs using a fielded NIC platform

**Solid spheres will be indirectly driven in a spherically convergent geometry**




*Closely related to the NIC Con-A platform (D. Hicks)*

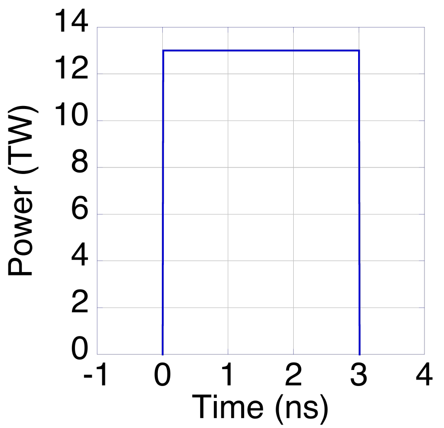
*(PI) R. Falcone, et al.*

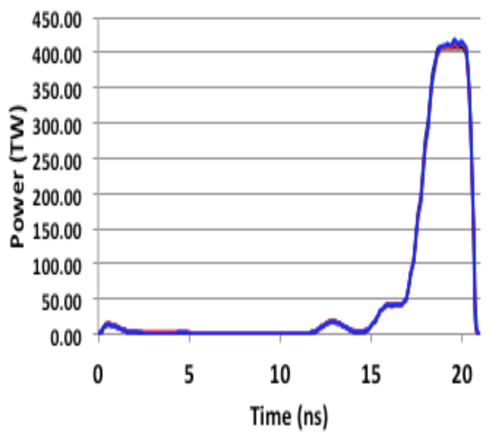
***Laser Requirements:***

***Drive :*** *6.9kJ/beam, 1.3MJ total (NIF ignition pulse (575)), focus= 1mm*

***XRTS probe and Radiography Backlighter (2 quads):*** *4-5 kJ/beam (NIF ignition pulse (575)), focus=500µm*

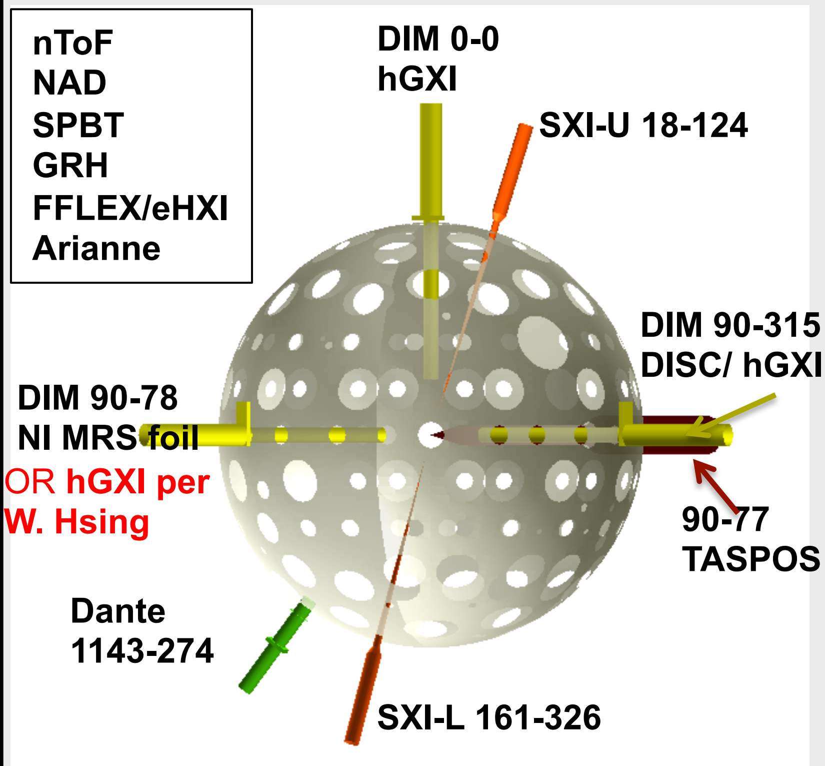
***BL (3ns) and Drive Pulse Shape (NIF):***



# Diagnostic configuration and compatible NIF platforms for Gbar pressure experiments

## DT4 for HDT & ConAW




***Diagnostics Configuration:***

| Diagnostic list | Location | Priority | Typ e | Calib |
|---|---|---|---|---|
| GXD or hGXI | 90-315 or 90-78 | Essential | 1 | Pre-Shot |
| hGXI +Supersnout 2 or MAHS | 0-0 | Essential | 1 | Pre-Shot |
| SXI 2 | 18,123 | Ride-along | 3 | Pre-Shot |
| SXI 1 | 161,326 | Ride-along | 3 | Pre-Shot |
| Dante 1 | 143,274 | Ride-along | 3 | Pre-Shot |

***Other compatible diag configurations:***

1) (DT4 for DT & ConAW) shown to the left
2) DT3 for DT & ConAW
3) DT2 for DT & keyhole

# The experimental choice of solid sphere target depends on transmission through the target and changes in opacity

***Compromise:***

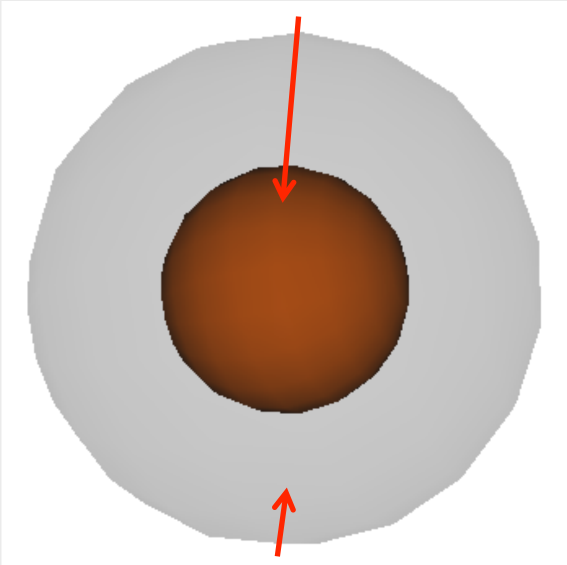
- Transmission through sample (small) vs spatial resolution (large).
- Compressible: more heating => worry about opacity falling.

***Best:*** C(diamond) with thick "ablator"

***Possible:*** C(graphite), BN, $B_4C$, with ablator; B or Be with or without ablator, doped CH

**Solid spheres are used instead of NIC capsules to better constrain the mass density through profile fitting**

Sample: diamond or graphite, 1 mm diameter



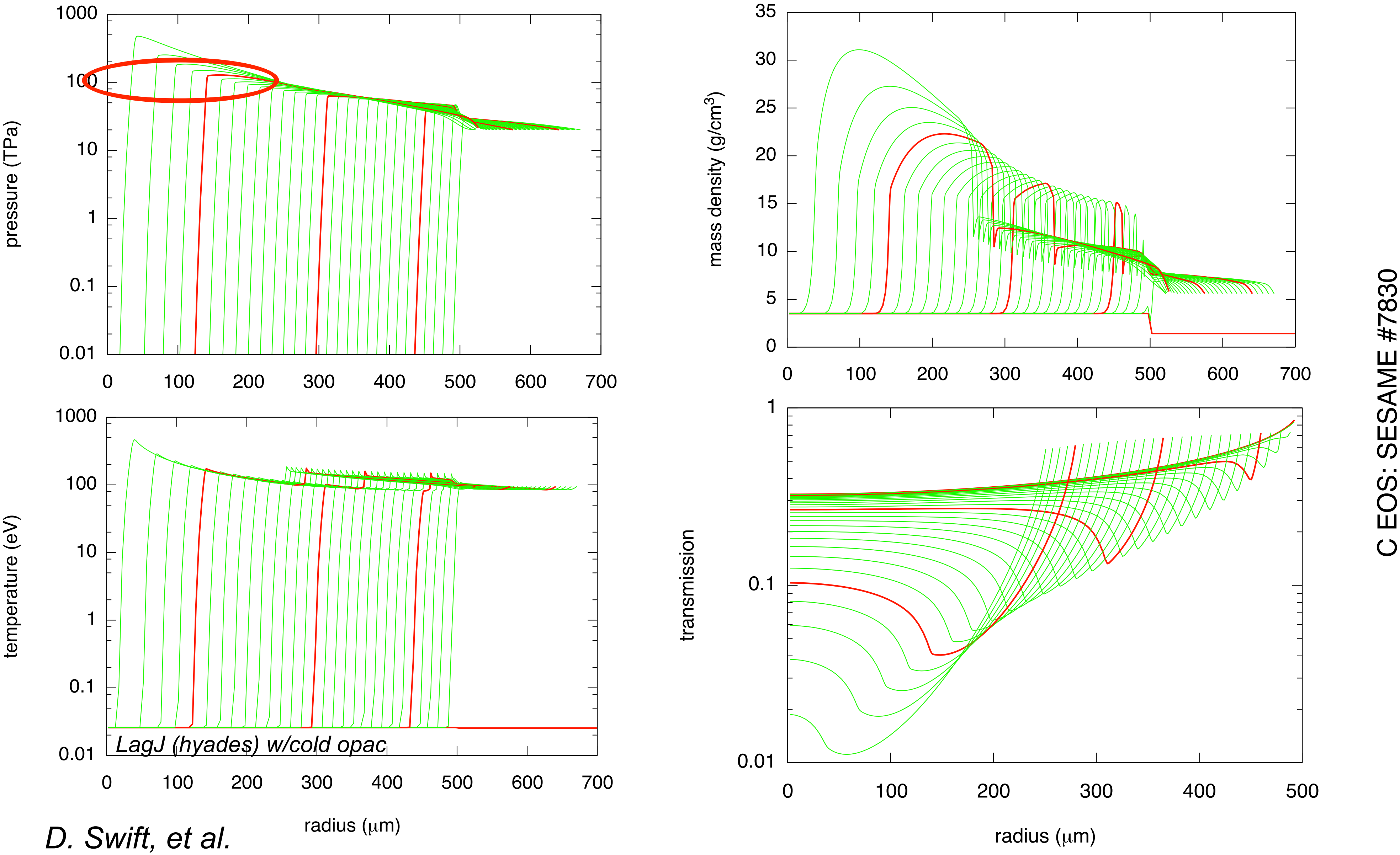
Ablator: CH, 2 mm diameter, doped with Ge/Br

*D. Swift, et al.*

**Diamond is also important for studying the structure of giant planets and advanced ICF ablator materials.**

# Rad-hydro simulations show that we can reach >2 Gbar pressures for indirectly driven solid* targets

*Carbon (dia) with thick ablator, 20 TPa drive




*D. Swift, et al.*

# A mass density profile of the sample can be determined from a radiographic image using Abel inversion

***Abel inversion***: An integral transform that can be used to reconstruct a mass density profile from a projected radiographic image.

Known (assumption): Initial x-ray intenisty

Measured: Observed transmitted x-ray intensity along LOS (y)

$$I(y) = I_0(y)e^{-\tau(y)}$$

Determined: optical depth along LOS (*y*)

Determined: Mass density profile

Determined (above): optical depth along LOS (*y*)

Known (assumption): Opacity profile at the BL energy

$$\kappa_\nu(r)\rho(r) = -\frac{1}{\pi}\int_r^\infty \frac{d\tau}{dy}\frac{dy}{\sqrt{y^2 - r^2}}$$

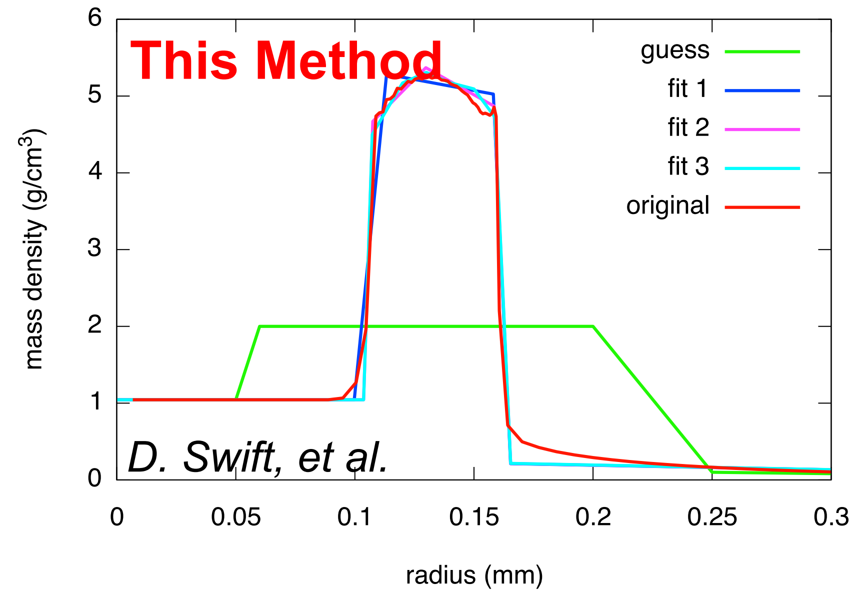
Measured: radius

*However… in addition to the assumptions, Abel inversion can amplify noise from photon statistics and backgrounds that is already an issue*

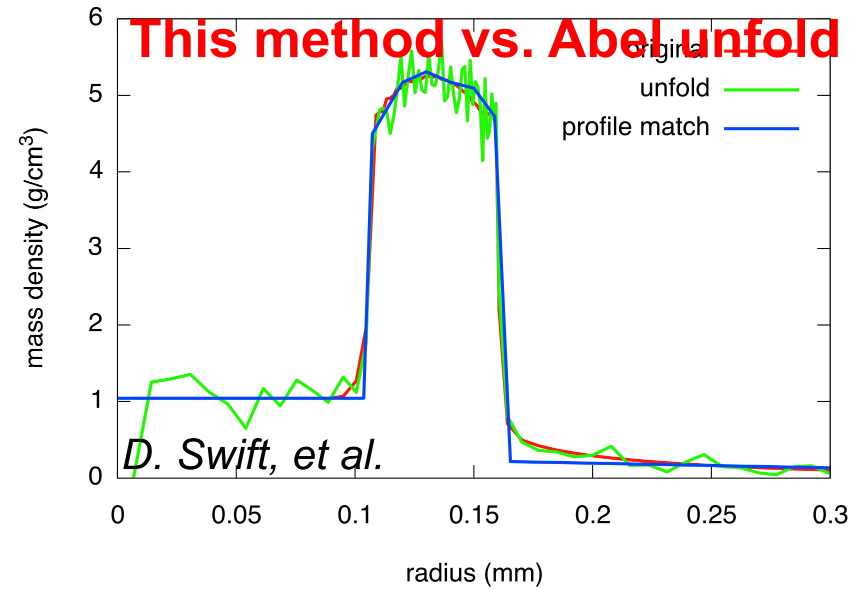
*D. Hicks, et al., PoP, 17 (2010)*

# We plan to use solid samples and profile matching with Bayesian analysis to determination the mass density profile

- ***Bayesian analysis:***
  - Use a density profile with adjustable parameters (e.g. nodes) and constraints
  - Simulate radiograph
  - Adjust parameters for best fit
  - Refine




- ***Solid Target:*** Using known unshocked density, captures shock jump much more accurately, even with noise and inaccurate profile of outer layers



# With the mass density profile determined and measured shock speeds we can constrain the EOS

***Rankine-Hugoniot Relations:***

$$D^2 = v_0^2 \frac{p - p_0}{v_0 - v}$$

$$u^2 = (p - p_0)(v_0 - v)$$

$$e = e_0 + \tfrac{1}{2}(p + p_0)(v_0 - v)$$

$D =$ Shock speed

$v = \frac{1}{\rho} =$ Specific volume

$p =$ Pressure

$u =$ Particle speed

$e =$ Internal energy

***Re-arrange D² relation:***

$$p = p_0 + \frac{D^2}{v_0^2}(v_0 - v)$$

$$\frac{\delta p}{p} = \frac{\delta(v_0 - v)}{v_0 - v} + 2\frac{\delta D}{D} \sim \frac{\delta \rho}{\rho} + 2\frac{\delta D}{D}$$

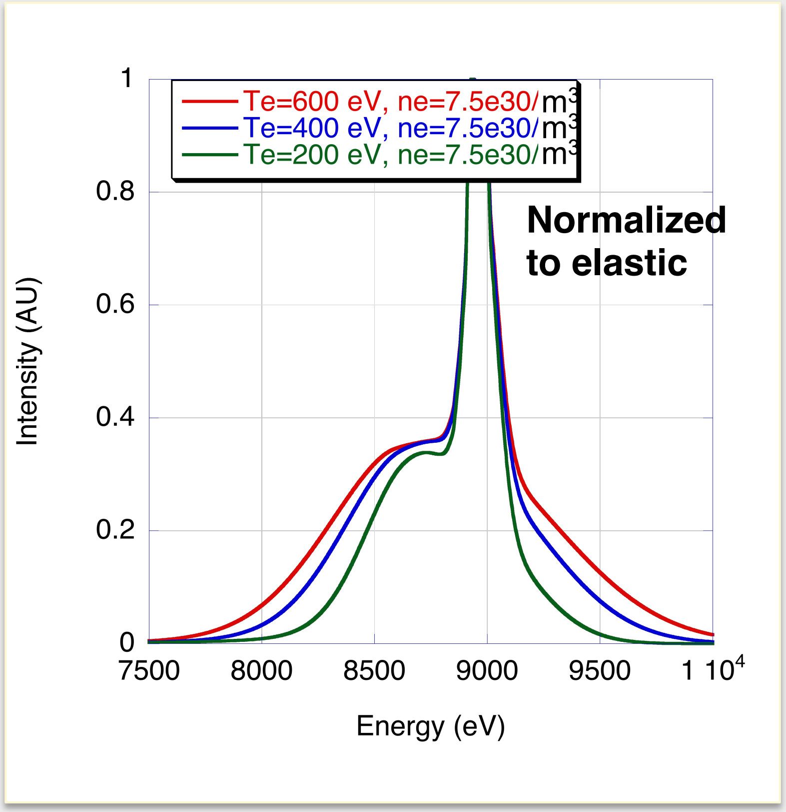
Only depends on:
- -***D***: Shock speed (measured)
- -***ρ***: Mass density (determined)
- -***P***: **Pressure** (inferred)

*R. Falcone, D. Swift, et al.*

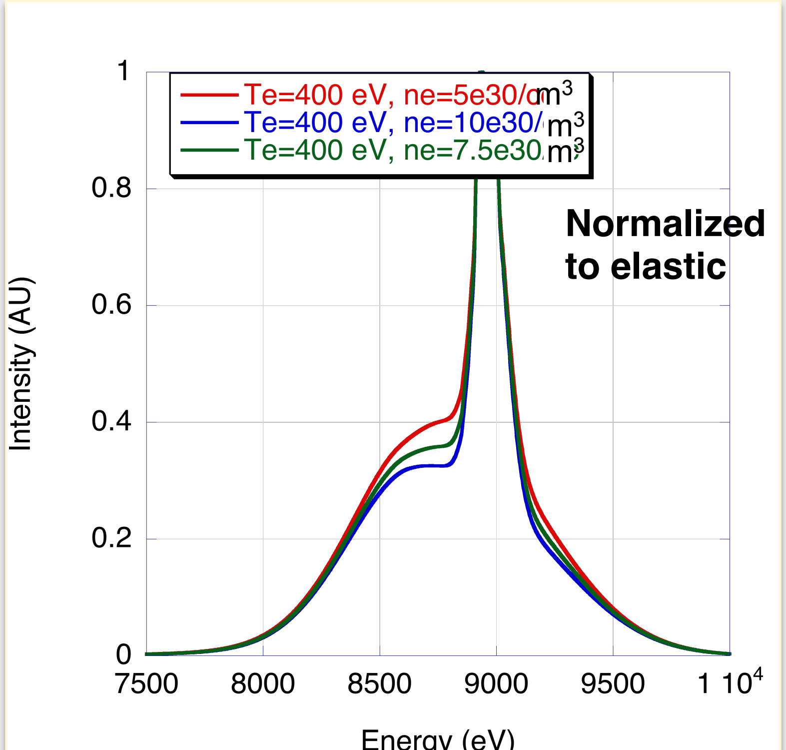
→ With ***P*** and ***ρ*** we determine the equation of state at Gbar pressures for CH and Diamond *(Other materials under consideration: Be, B, doped CH)*

# For non-degenerate plasmas the width of the Compton scattered feature is sensitive to Te

**Sensitivity of x-ray scattering to electron temperature**




**Sensitivity of x-ray scattering to changes in electron density**

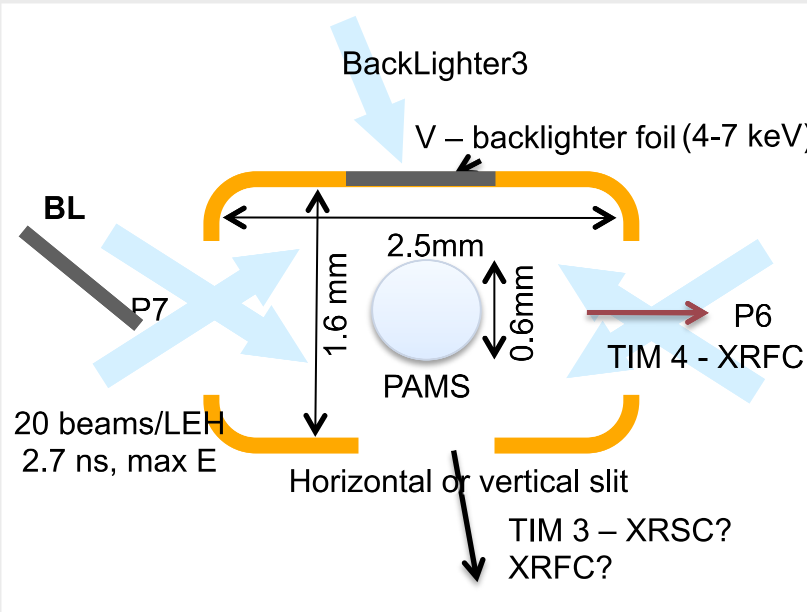



**Compton shift (eV)~154, TF (eV)~140**

***XRTS:*** is sensitive to temperature due to Doppler broadening in the non-collective regime at these temperatures and densities

# Current radiography experiments at Omega using solid spheres observe the shock front and initial densities have been estimated

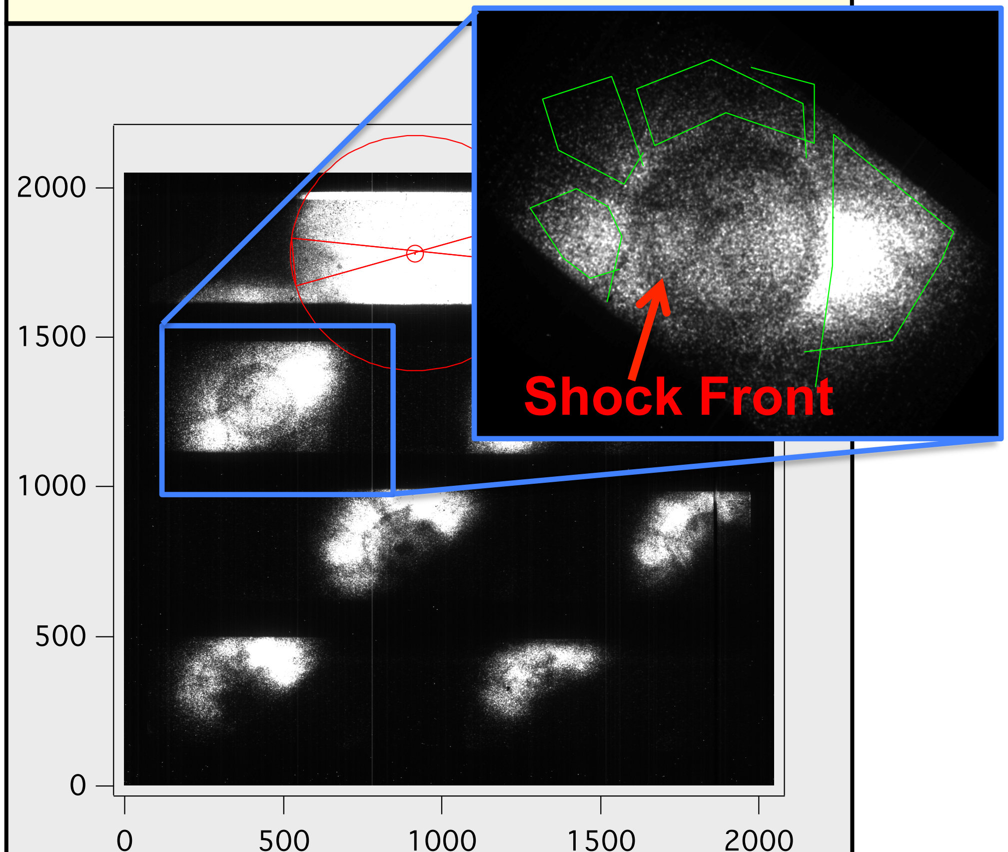
**Supporting Omega experiments are currently being fielded**




**T4-XRFC (2D radiograph), DANTE (Tr), T3-XRS (BL), SSCA (streaked radiograph)**

*J. Hawreliak, et al.*

**Measured radiographs of indirectly driven solid PAMS sample at Omega**




*Preliminary:* Meas. were in rough agreement with predicted shock velocities and shell thickness (LASNEX); inferred densities were lower than predicted

## Summary and outlook

- We have shown that the $n_e$ and $T_e$ for plasmas of densities of up to x13 times solid density can be accurately characterized with XRTS
- At NIF we plan to probe highly degenerate and compressed plasmas (20eV and 20x compression) and plasmas at high pressure and temperature (>1Gbar and ~0.4 keV)
- Other supporting Omega experiments probe the EOS of CH in a solid-sphere geometry *(J. Hawreliak)* and develop high Z backlighters such as Mo K-a and He-a *(T. Ma)*
- There have been many more XRTS and radiography experiments at Omega and Titan that investigate ion structure in 2x or 3x solid density plasmas at low temperatures

# The end.


NIF